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# Technology Evolution in Spacecraft Communications


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## ABSTRACT

A new computing paradigm is emerging with the advent of in-circuit reprogrammable Field Programmable Gate Arrays (FPGA). Low cost computers with CRAY-like processing power, can be built by combining multiple FPGAs in a parallel processing architecture. Together with the high performance front-end ingest and level-zero processing micro-circuits developed in-house at the National Aeronautics and Space Administration (NASA) These adaptive computers present a possible alternative to traditional CPU-based data processing systems. As long as the new technology offers an accessible application development environment that leads to lower cost and higher performance systems.

This paper discusses the evolution of the ground satellite communication systems and the efforts made by the Goddard Space Flight Center's (GSFC) Data Systems Technology Division (DSTD) to bring the science data from the satellite to the userís desktop. Primarily, it describes the next generation desktop system, itís architecture and processing

capabilities, which provide autonomous high-performance telemetry acquisition at the least possible cost. An analysis of the on-going research at GSFC and the usability of reconfigurable computing in the next generation of desktop satellite telemetry data processing systems is also discussed in the paper. Finally, the potential use of reconfigurable computing for level-zero and higher processing on board the spacecraft; and the planning processes and the applicability of new technologies for communication needs for the next century are evaluated and discussed in the paper.

## OVERVIEW

The Data Systems Technology Division (DSTD) at NASA Goddard Space Flight Center (GSFC) initiated a modular, product-oriented approach to developing ground telemetry and science data capture systems. This approach, based on an open-bus multiprocessing architecture, focused on the development of reusable "plug-and-play" processing modules in a flexible real-time operating system environment. Modules were developed using commercial VLSI Application Specific Integrated Circuit (ASIC) technology for high functional density, breakthrough performance, and low replication cost. To date, this low-cost technology has been used to support ground system implementations for over 20 different space missions/projects including the Small Explorer, Earth Observing System (EOS), Space Station, Deep Space Network, Hubble Space Telescope, Advanced Earth Observing Satellite (ADEOS), and Radarsat. Two generations of reusable processing modules have been applied to create systems for Time Domain Multiplexing (TDM) and Consultative Committee for Space Data Systems (CCSDS) packet formats at sustained rates up to 150 Megabits per second.

The principal function of a modern ground telemetry and command system is to act as a gateway between the a spacecraft and its associated ground support segment. In a typical environment, the telemetry gateway system serves as a bridge between data communications networks: the space-to-ground communications link and the ground communications network. Because of the wide difference between the two networks, the gateway is needed to act as a translator between each networkís distinct interfaces and protocols. The ground terminal provides the physical layer functions for space-to-ground communications. Gateway interfaces to the terminal are generally serial clock and data with the number of interfaces and channel data rates depending largely on the spacecraft. Different encoding formats and transmission techniques are usually used for uplink and downlink, and, as often is the case of high-resolution imaging spacecraft, downlinked housekeeping and sensor data can be on a separate channels.

Modularization took the form of encapsulating standard functions and interfaces into ìplug-and-playî subsystems within open-bus platforms. Product-orientation drove the need to create very low-cost functional modules that spanned the requirements of numerous missions. Through a continuous strategy of product development over several years, new generations of lower cost and higher performance modules incorporating even more functionality replaced older modules. This drove down system development cost, dramatically increased system performance, and allowed a common heritage among all deployed systems. A third generation telemetry system has been prototyped at GSFC. This High Rate Prototype (HRP) implementation uses a set of commercial and custom subsystem components based on state-of-the-art Very Large Scale Integration (VLSI) elements and advanced digital system technologies. The application of these technologies, together with standardized telemetry formats, make it possible to build systems that provide high-performance at low cost in a short development cycle. . The system architecture is based on the Peripheral Component Interconnect (PCI) bus and VLSI Application-Specific Integrated Circuits (ASICs). These ASICs perform frame synchronization, bit-transition density decoding, cyclic redundancy code (CRC) error checking, Reed-Solomon error detection/correction, data unit sorting, packet extraction, annotation and other service processing at rates of up to and greater than 150 Mbps sustained using a high-end performance Workstation running standard UNIX O/S, (DEC 4100 with DEC UNIX or better). ASICs are also used for (the digital reception of Intermediate Frequency (IF) telemetry as well as the spacecraft command interface for commands and data simulations.

The efforts expended to reduce the cost and increase the performance of ground processing systems have been primarily spent on the implementation of the level-zero satellite telemetry data processing stage. This development need to be extended to higher levels of the science data processing pipeline. The fact that level 1 and higher processing is instrument dependent, an acceleration approach utilizing ASICs is not feasible. A more flexible and programmable architecture which can be adapted to a variety of instruments is required. The advent of field programmable gate array (FPGA) based computing, referred to as adaptive or reconfigurable computing, provides processing performance close to ASIC levels while maintaning much of the programmability of traditional microprocessor based systems. The Adaptive Scientific Data Processing (ASDP) team at GSFC, has been studying the feasibility of utilizing adaptive computing to reduce the cost and increase performance of space-borne science data processing (level 1 and higher). Two applications have been prototyped, a level 3 and a level 1 algorithm, showing an order of magnitude acceleration over high-end workstations. A system is currently under development to merge the third generation level-zero processing system with an adaptive level-one processor. This ground system aims to achieve real-time data processing capability for the direct broadcast mode of the MODerate resolution

Imaging Spectroradiometer (MODIS) instrument to be flown abord the EOS-AM1 satellite in early 1999.

Reconfigurable computing also opens an avenue for the implementation of high performance processing elements on-board a spacecraft. The evolution of this technology can lead to the fourth generation of satellite telemetry processing systems. The traditional ground processing functions could migrate to the spacecraft, further reducing the cost of ground systems, a desired requirement to enable the widespread usage of a satellite's direct broadcast capability. The third generation high-rate level-zero processing system in combination with an adaptive level-one accelerator is further described in the next section followed by a discussion of the evolution to a fourth generation space-based system up to the ultimate space network concept.

## HIGH-RATE, LOW-COST GROUND SYSTEM

The Level-Zero processing of the ground system is implemented in the High Rate Prototype. The HRP performs the initial steps taken in the complex process of preparing telemetry data for delivery to NASA's customers. These steps are necessary to reconstruct data streams as they were at the output of the onboard experiments. This requires removal of all artifacts and disturbances introduced during data transmission through the space-to-ground network. Specifically, the following are considered the HRPís primary functions:

a. IF telemetry reception, demodulation, bit synchronization, and optional Viterbi decoding.
b. Frame synchronization, frame slip error detection, and identification of telemetry frames.
c. Reed-Solomon error detection and correction.
d. Extraction and reassembly of source packets.
e. Sorting and grouping of source packets.
f. Generation of quality, time correlation and accounting data.
g. Distribution of real-time packets, frames and data sets.
h. Uplink of spacecraft command data.
i. Simulation of telemetry data.
j. Remote spacecraft command capability.
k. Telemetry data storage with first-in last-out playback capabilities from disk.

The primary function of the HRP is to capture and process space telemetry and output frames and/or data packets out to an end user on a network interface. The telemetry stream is encapsulated within frames. The HRP will extract and reassemble the data units that are contained within frames. If requested, the HRP will distribute selected data units to users in real-time. The HRP will be capable of automatically sort the data it has extracted into separate files called data sets. The data units from a particular source are placed into a particular data set according to the configuration of the HRP. This source is identified by either the spacecraft identifier (SCID), virtual channel identifier (VCID) and application process identifier (APID) for source packets or SCID and VCID for other service units.

The HRP supports both the conventional CCSDS packet telemetry recommendation [1.5.1.a], which defines telemetry Transfer Frames and source packet formats, and the CCSDS Advanced Orbiting Systems (AOS) recommendation [1.5.1.b], which defines telemetry in the form of Coded Virtual Channel Data Units (CVCDU), AOS service units, and source packet formats.

The front end ingest of the analog data stream is performed by the Analog Front-end and the Digital Receiver subsystems. The Digital Receiver is implemented as a PCI card that will be housed within the HRP, as shown in Figure 1. The Analog Down-converter, or Front-end will be a separate module that will ingest the RF down-link from the spacecraft, perform the down-conversion, Doppler and frequency error correction prior to passing the IF telemetry to the Digital Receiver subsystem in the HRP. The Digital Receiver Card (DRC) Subsystem will be capable of receiving external analog telemetry through the external IF Telemetry Input Interface in the 52 MHz to 1 Ghz range. The card will process the input stream output decoded digital telemetry data and clock through the external Decoded Telemetry Data and Clock Output Interface. The DRC will be able to demodulate Binary Phase Shift Keying (BPSK), balanced Staggered

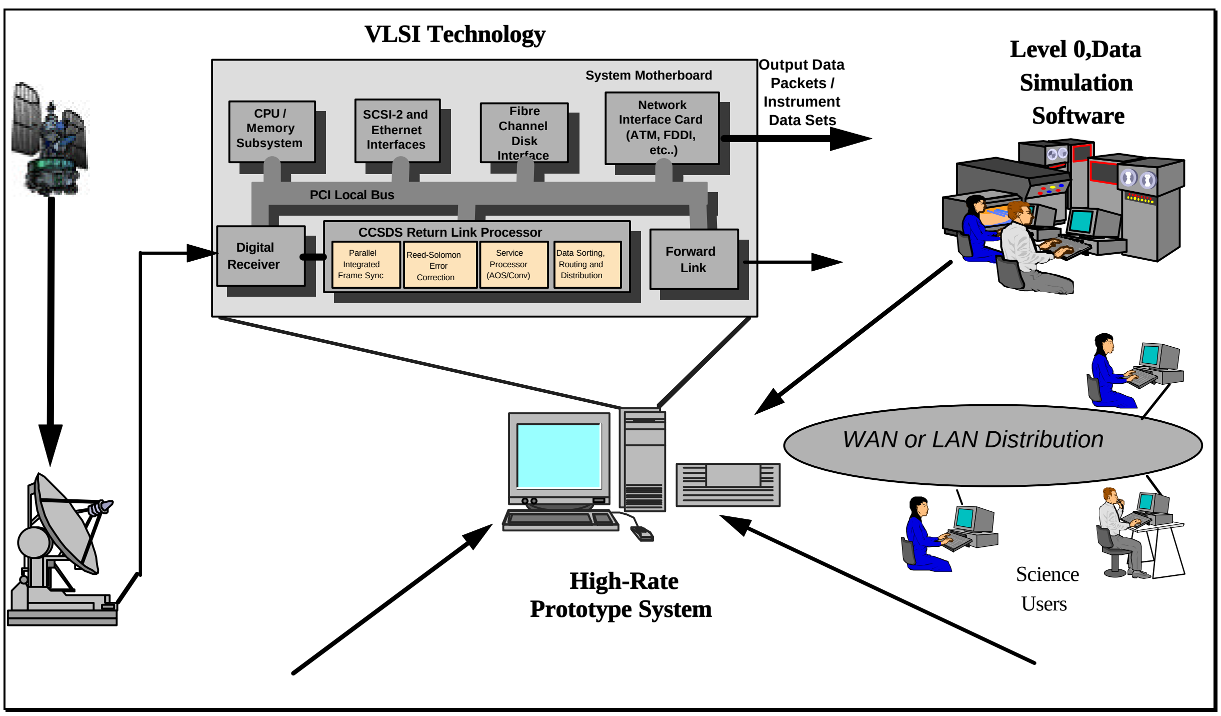


Figure 1. High-Rate Prototype

Quadrature Phase Shift Keying (SQPSK) and unbalanced Quadrature Phase Shift Keying (QPSK) telemetry; and be able to decode the telemetry with a bit error rate performance of within 1 decibel of theoretical Viterbi solution. In terms of performance, the DRC will be able to decode Non-Return to Zero Level/Mark/Space (NRZ)-L/M/S with no perceptible signal to noise ratio loss. At a system level, the DRC demodulate and decode an inherent telemetry data rate of from 1 Mbps to 150 Mbps per channel.

To provide the end-user, i.e. the scientist/principal investigator(PI) whose experiment is flying on the satellite, the data in the fastest possible time is the goal of this system. The faster the PI extracts the information from the raw telemetry data, the quicker the PI's response to the control center and the information users. For example, if the PI gets accurate information on the weather patterns suggesting a hurricane, the public is made aware of the information as soon as the analysis is complete. The level 1 and higher modes of processing which comprise the scientific information extraction process, are the most time consuming. The field of adaptive computing is in its infancy. This technology began with the creation of SRAM-based FPGA devices by Xilinx, Inc. in 1985. These devices can be reconfigured to perform a different function without removing the device from a circuit card or removing power from the system. Since then, FPGA device architectures have been continuously improving. Today, FPGA devices containing more than 100,000 logic gates, operating at rates above 80 MHz, are available. As semiconductor fabrication techniques continue to improve, larger and faster FPGAs will become available. Xilinx claims they will have 2 million gate FPGAs available by the end of the millenium.

By laying out several FPGA devices in a real-time configurable architecture it is possible to expand the number of gates available on an adaptive computer. Such systems are currently available from several vendors. They are referred to as adaptive accelerators, and are used to augment the processing capability of desktop and larger computer systems. An application may be partitioned between the host computer and the adaptive acclelerator, such that the computation intensive portions are implemented in the accelerator, and the user interface and data management functions are implemented in the host computer. The ASDP project has prototyped two satellite telemetry processing applications utilizing two different adaptive accelerators: a probabilistic neural network based multispectral image classification algorithm, and the MODIS reflective calibration algorithm. Both yielded an order of magnitude acceleration over the the traditional host processing system.

The MODIS instrument has a direct broadcast mode that enables users to receive the telemetry data directly from the satellite as it passes over. The ASDP group is currently developing an Adaptive Level One Accelerator (ALOA) system to process the MODIS geolocation and calibration algorithms at near-real time processing rates

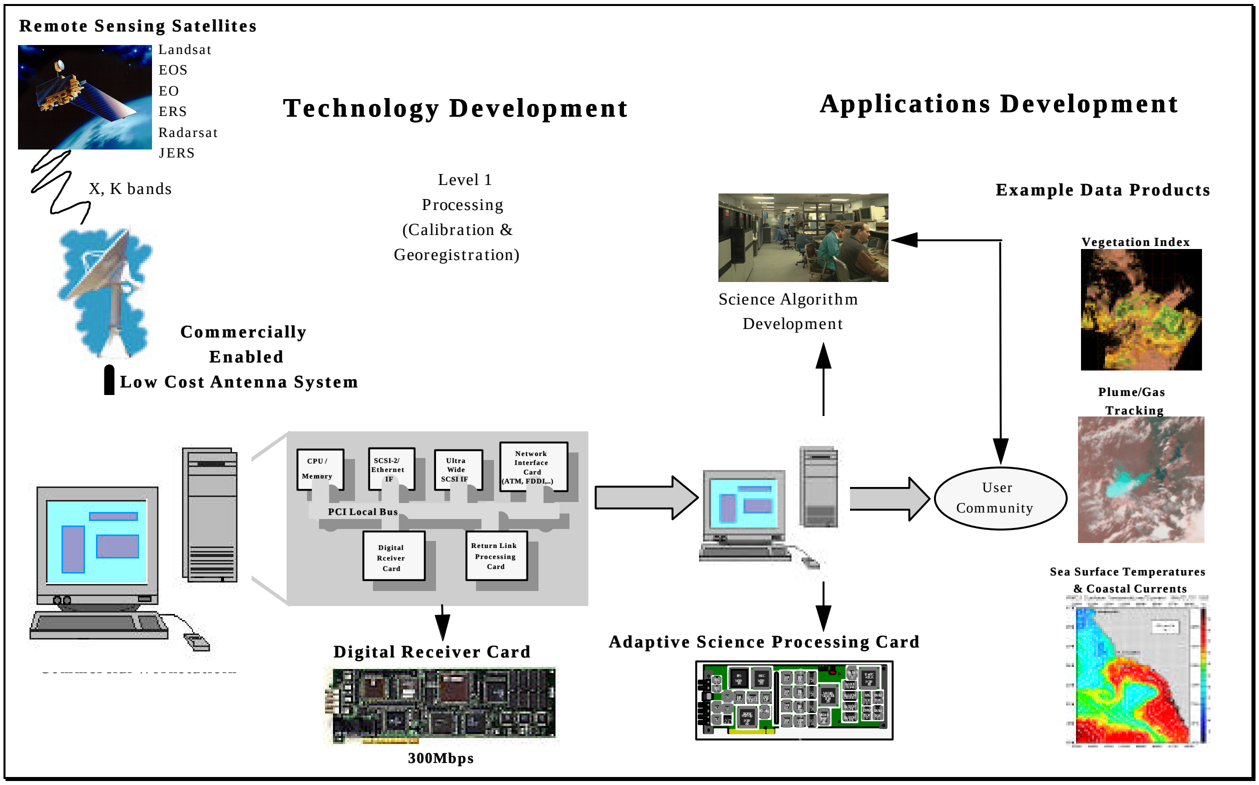


Figure 2. Regional Application Centers

The ALOA system will be combined with the front-end level-zero HRP system to provide a low-cost ground system capable of processing remote sensor data at Regional Application Centers (RAC). This application is illustrated in Figure 2. The goal being to bring high-performance processing capability closer to the user while reducing the cost by enabling the production of a larger number of real-time and robust scientific applications.

## HIGH-RATE SPACE-BASED SYSTEM

The fact that re-configurable computing by itís very name denotes the ease with which a re-configurable computing element can be made to adapt to new requirements opens a vista of uses for this technology. This paper prefaced the spacecraft to ground network as a communication gateway that made available data from space experiments to the end user. In this process, the mission statement is the process of transferring the raw data via telemetry to a ground system, extracting the usable information from this data, and providing it to the end-user in the fastest possible time. The conceptual ground system that has been prototyped at GSFC has achieved the latter half of the mission goal.

However, with higher data rates being envisaged for future missions, the cost and capabilities of the storage, Input/Output devices, and ground-based transmission devices are being stretched to the limit. The cost of storage though decreasing, is still high for the Fiber-Channel and high-end SCSI devices. Most commercial-of-the-shelf products are not ready with mature elements to meet the specifications. For example, the Fiber-Channel adaptor for the PCI-based machines is still in the beta stages of testing. Industry is still testing the device drivers for various platforms with select customers being targeted as beta-sites.

With these technological constraints, the researchers at GSFC strated investigating alternatives to accomplish the mission goals. It would be naive to believe that a trivial solution exists. The following paragraphs will explore two concepts that developers are investigating. As with telemetry, one force driving cost is standards. When common standards are recommended and accepted, the industry as a whole has a common specification to aim for which gives rise to wider competition and as a result better products.

Many papers have been written on improving the access of users to satellite data. Perrot[1] describes the option of using a satellite based connection to the internet, whereby large image data can be downloaded faster to the user. However, this option only examines the EO images which are currently on the internet. In fairness, it does advocate the use of COTS products such as the DVB/MPEG2 receiver cards for the PC based user terminal, and standard TCP/IP protocols. In another paper[2] the authors describe an operational scenario for the transference of medical information using a satellite network. Once again, though the paper does advocate the use of emerging standards in medical image transmissions and the use of TCP/IP, it is restricted to a specific type of data transmission.

The GSFC initiative[5] is outlined in the Concept of Operations. The models described by SAIC are driven by cost reductions in life cycle costs for mission support. The document summarizes how the costs for space/ground contacts can be achieved, by focusing on three essential areas, namely, (1) network scheduling automated procedures, (2) reduction in operational staffing levels, and (3) the standardization of downlink data acquisition and uplink data transport. The document points out the idea of using a “smart interface/virtual system” concept on-board the spacecraft. For example, implementing a file transport and management capability on-board the spacecraft and using file transport protocol to move data from the spacecraft to the ground, from the ground to the spacecraft, and between the spacecraft and the instrument(s)/payload(s) [note: payload refers to the onboard experiment].

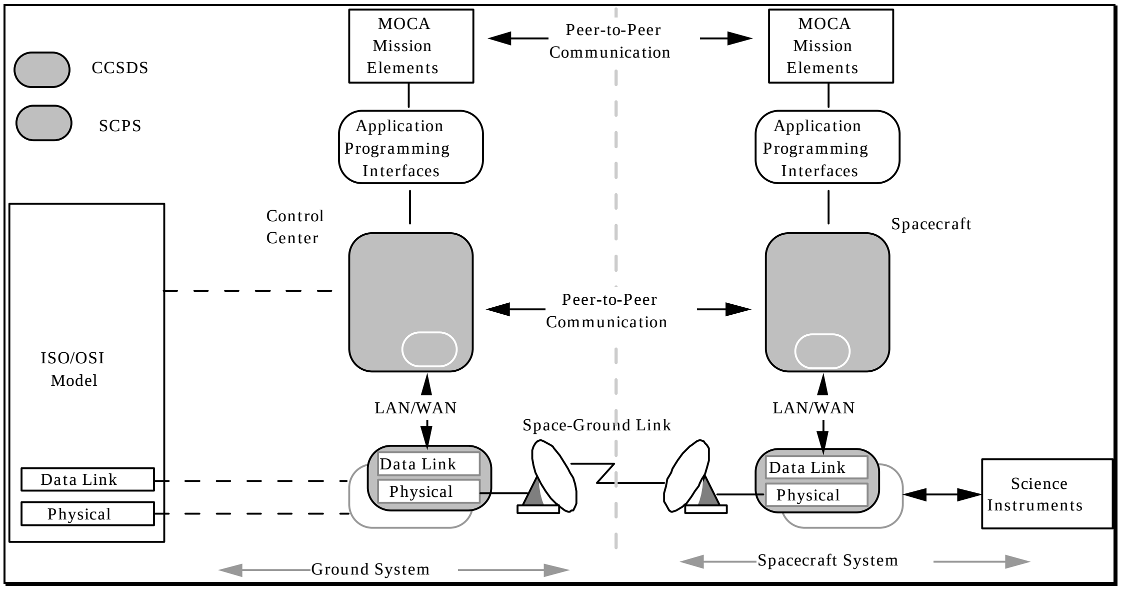


Figure 3 End-To-End Communication Model

The MOCA interfaces are based upon service request flows and data product transfer flows. The concept points out that MOCA provides a mechanism such that these flows are also based upon the client/server model and file transfer protocol concepts, and allow the MOCA infrastructure to look like a virtual and logical system to the user. One such architectural model to achieve this concept is the End-To-End Communications model described in the document. Essentially it is based on existing stable standards and uses standard space-to-ground protocols as well as promising protocols under development, Figure 3.

The IPIC concept[7] outlines a two step approach for low cost, high rate data communication between the end-user and the spacecraft. In this concept the MOCA approach of using existing standards and rapidly developing and emerging standards are stressed. IPIC calls for prototyping and exploring the model that recognizes satellites as “nodes on a network”. The concept strongly recommends the use of industry-based standards and communication protocols.

## CONCEPTUAL SPACE NETWORK SYSTEM

It is obvious from literature that a lot of work is being done in implementing the network in the sky scenario to bring the science investigator closer to the data that is being observed. With the strides being made in space-to-ground communication standards and network communication protocols, the day is not far when the infrastructure will be in place for easy access to experimental data.

However, the rapidity of the scientific information transfer to the end-user is based on how fast one can extract the information from the data. The emerging data standards would make available the raw data to the user, but the data analyst has to de-encrypt the data to extract the images or other forms of data to be able to analyze the information. This section proposes a concept, whereby all the experimental data gathered aboard the spacecraft will be processed at some point in time before being made available to the end-user.

The concept is essentially a level 1 and upward data processing element that will be implemented between the user and the network node. This network node may be either in space using the "satellite node on the network" concept[7] or may well be the "Satellite Gateway Server" concept[1]. In either case the processing element will be a design based on a three element PCI-based computing system capable of ingesting instrument data and extracting level 1, level 2 upwards data. This data will be made available to the end user using the newly developed SCPS[5] or "Skinny Stack for Space Systems". NASA and DoD have decided to jointly design, develop, and implement a common protocol. This protocol stack, will be placed on top of CCSDS, to provide a full suite of communications services for space use. The full stack is supposed to enhance the capability of not only communicating between different spacecraft, but also between spacecraft and the end users. The cost saving in re-use and standard communication protocols will result in tremendous cost savings for space and ground systems. As stated in the Concept Document[5], the SCPS will initially provide the protocol mechanisms to transport data files; and most data transfers between space and ground resources can benefit from implementation of a File Transport Protocol.

Figures 4 and 5 depict two concepts for the Space Network System. Figure 4 implements the high-rate ground based system, i.e. "Satellite Gateway Server" concept, the essential difference being that the extracted information is made available to the science user at least a magnitude faster than the traditional ingest-now and process-later paradigm. Figure 5 pushes the envelope even further and carries the processing elemet on the spacecraft. This concept is based on the SCPS vision, the essential difference being that the data files are extacted data formats and as such available to the user at least a magnitude faster in time.

## CONCLUSIONS

The advent of new tchnologies and NASA's credo for using them, has opened up a new vista for bringing information back to the science user. The Moderate Resolution Imaging Spectroradiometer (MODIS) instrument is one the five instruments on-board the EOS AM-1 spacecraft. More than 50% of the 918 Gigabytes of data generated per day will be from this instrument. The host platform used for evaluation was a Silicon Graphics Origin 200 workstation, similar in CPU power and memory configurations to that used by the data archiving centers for the EOS AM1 ground system.

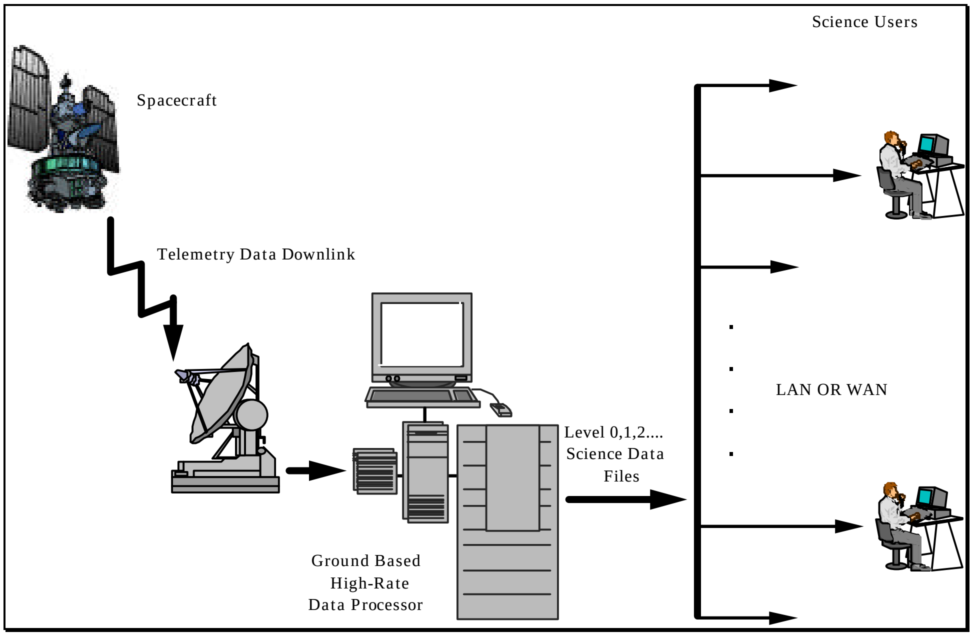


Figure 4 Ground-Based High Rate Data Processing System

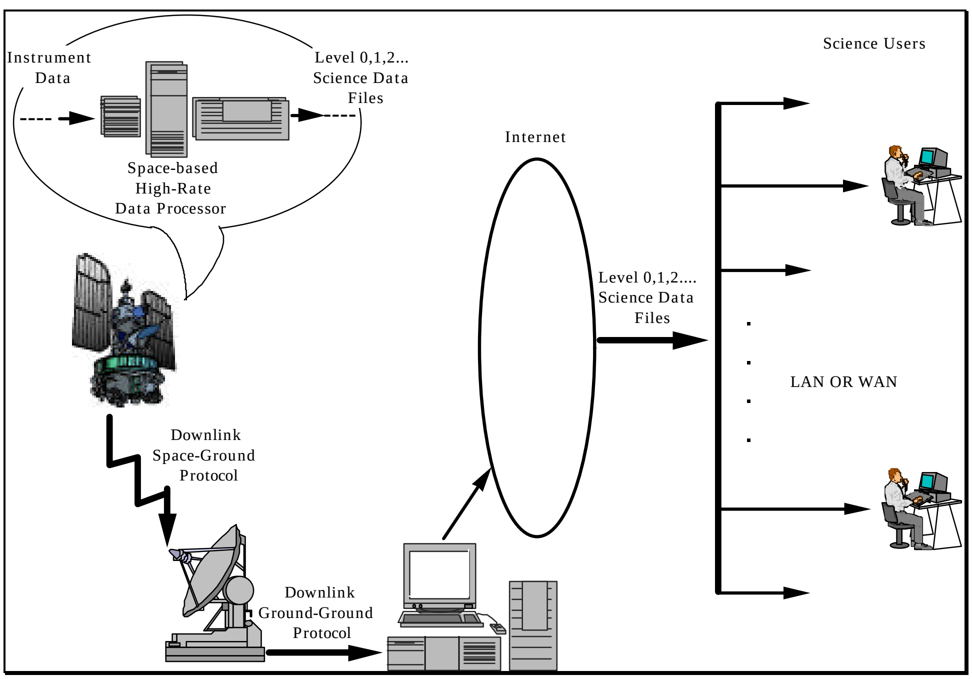


Figure 5 Space-Based High Rate Data Processing System

This provided a benchmark to evalute the impact of inserting adaptive computing into this environment. The results[8] from the MODIS reflective calibration demonstration are shown in Table 1. The software version, that will be running on the ground system archiving center workstations, took 16.51 seconds to complete the reflective calibration function; while the FPGA version took only 1.78 seconds. This demonstrated a performance improvement greater than 9 times for the FPGA option over the traditional software only version.

| Reflective Calibration Implementation Method | Time (secs) |
|---|---|
| Software Only | 16.51 |
| FPGA Co-processor | 1.78 |
| Performance Increase | 9.28 |

Table 1 MODIS Comparison Results

In addition to the performance improvement, the added advantage of in-line re-programming of the FPGA devices for new requirments or new missions gives a very quick turn-around in support systems. This results in a tremendoes cost benefit both in replication and schedule costs.

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